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Non-destructive compositional analysis of historic organ reed pipes

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Abstract
In order to be able to reproduce historic organ reed pipes, a bulk non-destructive chemical composition analysis was performed on the tongues and shallots, focusing mainly on the ratio between copper and zinc and on the presence of lead. Prompt gamma activation analysis results allowed us to observe for the first time that the ratio between the two main components of the brass alloy changed from Cu:Zn = 3:1 for the old tongues and shallots to Cu:Zn = 2:1 around the middle of the 18th century, which is typical also for the modern alloys offered to the organ builders nowadays. We also discovered that the Pb content in the old historic brass alloy diminished until the middle of 18th century when the brass alloy became mainly Pb free.
The non-uniform lead distribution inside one of the shallots obtained from a prompt gamma activation analysis (PGAA) experiment was studied by neutron tomography. It gave us a three-dimensonal (3D) distribution of the lead inclusions inside the shallots. The lead particles are concentrated towards the base of the shallot.

1. Introduction and theoretical aspects

The organ (figure 1), one of the most sophisticated musical instruments, is an important symbol of European culture. No other musical instrument can compare with the pipe organ in power, timbre, dynamic range, complexity of tone and sheer majesty of sound. The organ evolved through craftsmen slowly accumulating and applying empirical knowledge until the end of 17th century, when the organ attained its modern form. At the beginning of the 19th century during industrialization, the technology of organ production changed drastically [1]. Combined with a transition in music from baroque to the romantic style, this led to an essential change in the sound of organs and organ builders in the 19th and 20th centuries, oriented towards the sound of 'new' music. The recently appearing interest in baroque and medieval music led to demand in the market to produce new organs with an old sound. Because old technology based on intuition and the family tradition of organ masters was lost, new technology has to be developed, based on the most modern analytical possibilities and achievements of materials science, as it is known that the alloy composition and properties of the pipes strongly influences the organ's sound [2, 3].

An organ contains flue and reed pipes constructed of lead–tin alloys (figure 2). There are no moving parts within a flue pipe. Reed pipes (figure 3) contain an additional vibrating part, the Cu-based alloy tongue that vibrates on the shallot and crucially influences the sound—see the scheme of a reed pipe in figure 4.

In most cases, both tongues and shallots are made of brass (a copper–zinc alloy). The ratio between Cu and Zn in the brass alloy and the presence of Pb were of prime interest in our study, due to their essential influence on the sound that is obtained.

In order to have a good understanding and to be able to have a European-level overview of the situation, we analysed a large number of brass tongues and shallots from different areas of Europe.

Different kinds of experimental analyses were carried out, such as microstructural characterization of the tongues and shallots by optical and scanning electron microscopy [4] or residual stress measurements by synchrotron radiation diffraction [5].

Figure 1. Casparini organ in Vilnius.

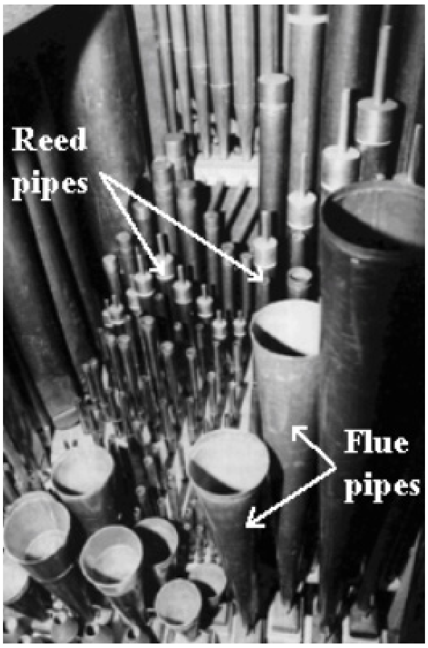


Figure 2. Flue pipes and reed pipes.

In this work, prompt gamma activation analysis (PGAA) was used to obtain a chemical analysis of the bulk material in a non-destructive way.

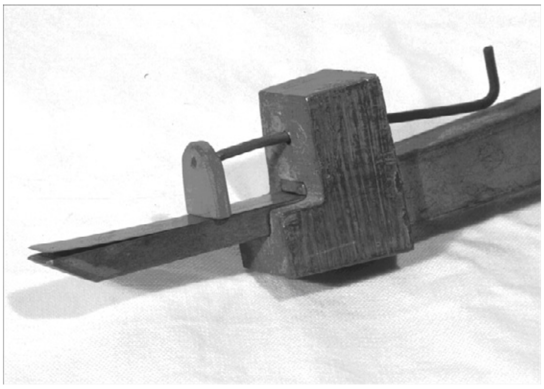


Figure 3. Reed pipe.

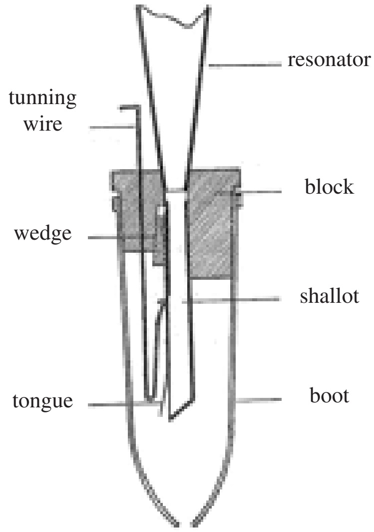


Figure 4. Scheme of a reed pipe.

By PGAA, a simultaneous determination of both the presence and the amount of different elements in the analysed specimen can be obtained. The sample is continuously irradiated with a neutron beam. The constituent elements of the sample absorb some of these neutrons and emit prompt gamma rays which are measured with a high-resolution gamma-ray spectrometer. The energies of these gamma rays identify the neutron-capturing elements, while the intensities of the peaks at these energies are proportional to their concentrations. The amount of an element is given by the ratio of the count rate of the characteristic peak in the sample to the rate in a known mass of an appropriate standard material, irradiated under the same conditions.

For one of the analysed shallots we considered three different measuring points to verify the presence of any distribution in the chemical composition inside the shallot. No difference (within experimental errors) in the Cu–Zn ratio from one point to another was detected, but there was an essential difference concerning the Pb content; this is why we decided to perform a neutron tomography (NT) experiment to study the lead inclusions inside the brass material in one of the shallots.

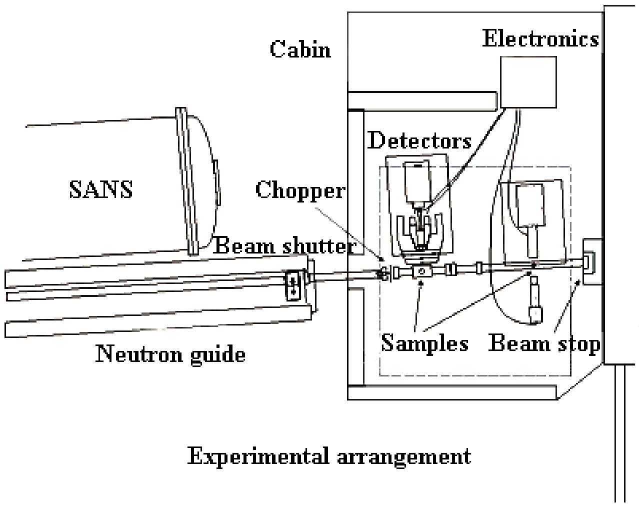


Figure 5. Scheme of the PGAA instrument at Budapest Neutron Centre (BNC).

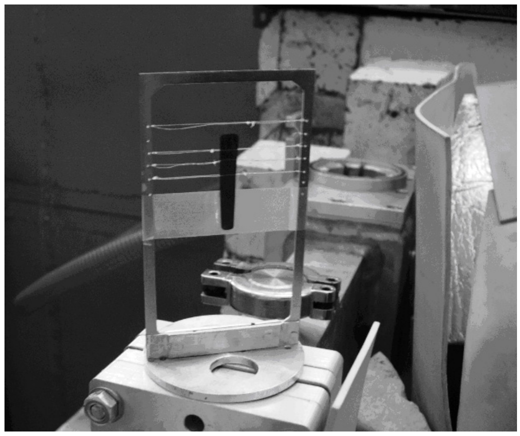


Figure 6. Tongue fixed on the sample holder (BNC experiment).

Neutron tomography is a non-destructive technique that allows a 3D reconstruction of the analysed specimen, based on measuring the absorption coefficient contrast between different areas of the specimen. In other words, many radiographs of the samples are taken at different angles with respect to the incoming neutron beam, so that a large number of projections of the specimen are obtained; the 3D reconstruction is then performed using an inverse Radon transform algorithm.

2. Experimental details

2.1. Analysed specimens

Historic brass tongues, produced between 1624 and 1889, were made available by organ builders from nine European Union (EU) countries (France, Belgium, Germany, Italy, Latvia, Lithuania, Netherlands, Sweden and the UK). We analysed almost 40 historic tongues. Additionally, two modern brass alloys were measured.

Four historic brass shallots from Germany and the Netherlands (18th century) were also analysed.

The average dimensions of the tongues were 100 mm $\times$ 10 mm $\times$ 0.5 mm, while the average dimensions of the analysed shallots were 150 mm $\times$ 15 mm $\times$ 15 mm, with a thickness of the shallot walls of about 1 mm.

We analysed all the tongues and the shallots in their middle, and we selected one tongue (Överselö church, Sweden, 1754) and one shallot (St. Marienkirche church, Stralsund, Germany, 1659) in which we analysed three different points to see if there is any difference in the chemical composition between different areas of the tongue and shallot.

2.2. PGAA experiment at Budapest Neutron Centre

In figure 5, the scheme of the experimental setup is presented, while in figure 6 the sample holder fixing the tongues and shallots in a vertical position is shown. The collimation of the beam was realized by a 1 $\times$ 1 mm^2 slit for thicker samples and a 2 $\times$ 2 mm^2 slit for the thinner ones. The measurements were performed in vacuum (1 mbar), in order to reduce the background effect. The sample-to-detector distance was 230 mm and the neutron flux at the sample position was 5×10^7 neutrons cm^{-2} s^{-1}.

2.3. NT experiment at CONRAD instrument, Hahn-Meitner-Institute, Berlin

NT experiments were performed at the CONRAD facility, situated at the end of a curved neutron guide facing the cold source of the BER-II reactor, at the Hahn-Meitner-Institute, Berlin, Germany. The neutron guide provides a cold neutron flux at the sample position of approximately 10^7 neutrons cm^{-2} s^{-1}, with negligible γ-radiation and fast neutron background. The available beam size at the sample position is 10 $\times$ 10 cm^2. The detector system is based on a 16-bit Peltier-cooled CCD camera (Andor DW436N-BV) with 2048 $\times$ 2048 pixels. The images obtained from the LiZnS scintillator are projected via a mirror and a lens system onto the CCD chip (figure 7). The 3D tomograph was obtained from 300 radiographs at different projections covering 180° (0.6°/projection). The estimated geometrical resolution was about 200 μm/pixel.

3. Results and discussion

From the PGAA analysis we found that in the old historic brass tongues and shallots (period 1624–1790) the concentration of the main components, i.e. copper and zinc, varies in a very narrow interval of just a few per cent around Cu:Zn = 3:1 (figure 8). A higher zinc concentration of approximately 33 wt% additionally appears around 1750. These two concentrations coexisted for about 40 years. From the end of the 18th century up to the present day, the Cu:Zn ratio remained approximately constant at 2:1. This ratio was also obtained for the two modern brass alloys. In figure 8 the errors are also reported: the experimental error related to the measured Cu:Zn ratio (vertical axis) and the error related to the uncertainty in the year in which the tongue or shallot was manufactured (horizontal axis).

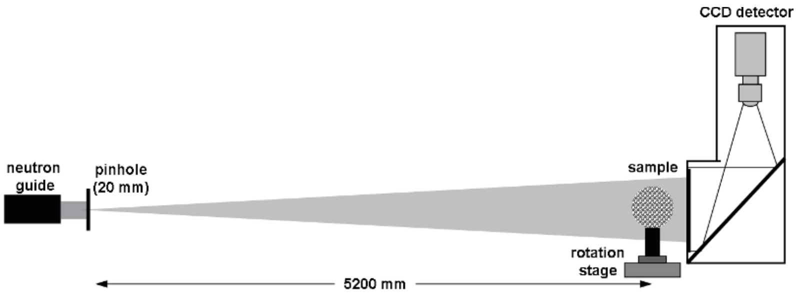


Figure 7. Experimental setup for neutron tomography experiment at CONRAD, HMI.

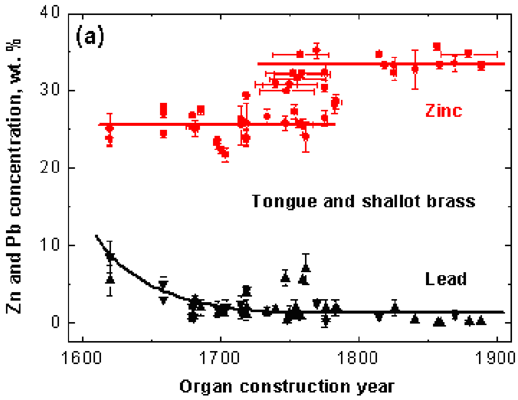


Figure 8. Zn and Pb concentration in brass tongues and shallots from historical organ reed pipes.

(This figure is in colour only in the electronic version)

Another important aspect is the Pb content of the tongues and shallots, which influences the microstructure and thus the sound. Tongues and shallots always contained lead before 1750. The concentration of lead decreased from 7–8 wt% in 1624 to 2 wt% in the middle of the 18th century (figure 8). The first lead-free tongues appeared around 1750. After 1820, lead completely disappeared from the brass alloy which is still the case in the majority of modern brass nowadays. The disappearance of lead from brass alloys is probably connected to the fact that Pb results in brass embrittlement and makes mechanical treatment like forging and rolling more complicated.

We analysed one tongue and one shallot in three different areas in order to see if there is any difference in the chemical composition between different areas of the tongue and shallot. For the analysed tongue we observed no difference (within the experimental error) in both the Cu–Zn ratio and the Pb content for the three different areas considered, while for the shallot there was no difference in the Cu–Zn ratio but there was a significant difference in the Pb content: 1.6 wt% in the middle of the shallot and 12.9 wt% at its lower end. As observation by microscopy gave us no indication of the presence of Pb on the surface of the shallot, we decided to perform a neutron tomography experiment for a better understanding of this high Pb concentration value.

We analysed the shallot using neutron tomography and we observed that in the lower part (left-hand side) of the shallot there were big Pb inclusions (darker colour), as one can observe in figure 9. In this figure the three-dimensional distribution of the absorption coefficients in the shallot is visualized using the VGStudio MAX 1.2 software.

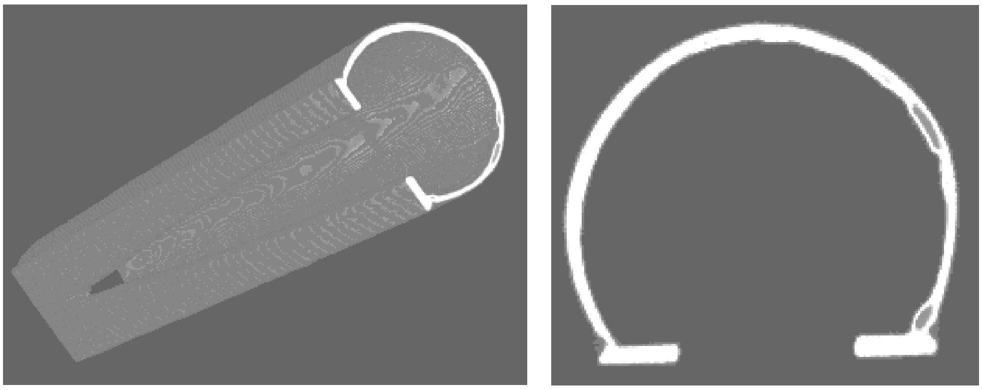
From both microscopy and neutron tomography (figure 10) we observed that the Pb inclusions are inside the brass alloy and not on the surface of the shallot. One possible explanation is that Pb 'falls' towards the shallot bottom, due to a sort of time-induced creep.

4. Conclusions

To our knowledge—from an internet survey and speciality literature research—this is the first time that systematic work has been carried out on analysing the Cu:Zn ratio and the Pb content of organ reed pipes and on describing its evolution in time from the beginning of the 17th century up to nowadays for different European areas. Also, it is the first time that the change in the Cu:Zn ratio from 3:1 to 2:1, together with a decrease in the Pb content until its disappearance from the brass alloy, was observed, both happening around the middle of the 18th century.

The prompt gamma activation analysis method was essential in giving us in a non-destructive way of gaining information on the bulk chemical composition of the tongues and shallots. Neutron tomography allowed us to visualize the Pb inclusion inside the analysed shallot. Neutron tomography

Figure 9. Absorption contrast—presence of Pb inclusions in the bottom region (darker colour, left-hand side).



(a) (b)

Figure 10. 3D reconstruction (a) and axial projection (b) of the investigated shallot.

will be used in our future measurements to investigate the Pb distribution inside the shallots and to verify the hypothesis of time-induced creep of the Pb inclusions in the brass matrix, the Pb inclusion being observed in the bottom part of the shallot that we analysed.

The difference in the Cu–Zn ratio and Pb content between old and modern brass, together with information on the manufacturing techniques (casting, hammering–annealing cycles, filing) obtained from microstructure, texture and stress analysis, allowed the production of a brass alloy with a similar composition to the old historic brass. This permitted organ builders to manufacture tongues that produce a sound similar to the old sound of historic organs when put in a reed pipe and sounded. The results of the present research have already been put into practice by using the novel alloys for tongues in new organs in the baroque style, currently under construction for the Noorderkerk in Rijssen (The Netherlands) and the Korean National University of Arts in Seoul (South Korea).

Acknowledgments

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